

Liver injury: What you need to know

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ABSTRACT:

The liver is the most commonly injured abdominal solid organ regardless of mechanism. The majority of liver injuries are grades I to III, with 12% to 20% as grades IV and V. In the hemodynamically stable patient or prompt responder to resuscitation, 85% to 90% of blunt liver injuries can be managed nonoperatively, regardless of the grade of injury. The promulgation of nonoperative management has resulted in decreased overall mortality for blunt liver injury. On the other hand, over the past 30 years, major advances in resuscitation science, intensive care, damage-control surgery, and nonoperative adjuncts have done little to reduce the operative morbidity and mortality of grades IV and V liver injuries. Angiography with embolization is often effective in stopping bleeding. However, angioembolization confers additional risk of complications (i.e., major hepatic necrosis and sepsis). This review will briefly present critical surgical anatomy and grading systems for liver trauma, followed by organ-specific diagnostic, resuscitation, and triage considerations. It will review important limitations, risk factors for failure, and complications associated with nonoperative management and angioembolization. This article presents operative techniques and pearls for surgical treatment of the most severe injuries, including adjuncts for hemorrhage control. Finally, we suggest the 6 Ps as an operative strategy for liver injury: Push-Pack-Pringle-Put Back-Phone-Pivot. (*J Trauma Acute Care Surg.* 2025;00: 00–00. Copyright © 2025 Wolters Kluwer Health, Inc. All rights reserved.)

LEVEL OF EVIDENCE:

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KEY WORDS:

Liver trauma; liver injury; nonoperative management; operative management.

The liver is the most commonly injured abdominal solid organ regardless of mechanism owing to its large size, position, abundant blood supply, and fragile parenchyma.¹ The surgical treatment of hepatic trauma has evolved from early World War II-era conservative therapy including intraparenchymal packing, to definitive surgical management by resection during index exploration in the 1970s, to widely adopted nonresectional and damage-control techniques through the 1980s and 90s.^{2–6} Improvements in hemostatic resuscitation, intensive care, and the advent of angiography with embolization resulted in proliferation of nonoperative management (NOM) for liver injury regardless of grade.¹ Several studies throughout the 1990s demonstrated the safety of NOM for most liver injuries.^{7–9} Following a worldwide paradigm shift toward liberal use of NOM, even high-grade injuries were successfully managed nonoperatively and demonstrated superior liver-specific mortality compared with operative management.^{9,10}

We continue in the era of NOM and nonresectional therapy in our approach to liver injury. Successful management of these complex injuries requires the expertise of trauma surgeons, hepatobiliary or transplant surgeons, intensivists, transfusion medicine physicians, interventional radiologists, and gastroenterologists.¹¹ Currently, over 85% to 90% of blunt liver injuries

are managed nonoperatively. Our review of the 2022 American College of Surgeons Trauma Quality Improvement Program found 26,592 liver injuries in adults with 78% blunt and 22% penetrating mechanisms of injury. Overall distribution of liver injury by grade was 57% grades I/II, 22% grade III, 15% grade IV, and 6% grade V. Nonoperative management was applied in 89% of blunt injuries (Table 1). Mortality among patients managed with NOM after blunt liver injury was 6% overall. Operative mortality for blunt injuries was substantially higher than penetrating mechanism at every grade.

Consequent to this increased reliance on NOM and in accordance with the infrequency of exsanguinating liver trauma overall, operative experience with hepatic trauma has dwindled.¹² High-grade liver injuries requiring operative intervention represent only a small minority of all hepatic injuries; even among these, only about 15% require a complex procedure beyond packing.¹³ This extrapolates to only 2.5% of all liver injuries requiring anatomic resection or major venous repair. Additionally, most general surgery trainees have limited exposure to elective complex hepatobiliary surgery and report that they would require additional subspecialty training before achieving comfort with hepatobiliary surgical procedures in their own practice.¹⁴

It is not surprising that complex liver injury has a persistently high operative mortality. Severe parenchymal, hepatic venous, and juxtahepatic caval injuries (grades IV and V) have operative mortality rates from 50% to 100% in most series.^{15–17} Their infrequency underscores the importance of surgeon preparation for early recognition of life-threatening complex liver injuries. This review will provide a brief description of critical anatomy and grading systems necessary to establish a common nomenclature, review diagnostic and resuscitation considerations specific to liver injury, present contemporary data regarding outcomes of NOM, describe risk factors for failure of NOM, and outline the role for catheter-based angiography and

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TABLE 1. Liver Injuries (N = 26,592 Adult Liver Injuries)

	Grades I/II	Grade III	Grade IV	Grade V
Blunt liver injury, 20,668 (% of blunt injuries)	12,155 (59%)	4,728 (23%)	2,801 (13%)	984 (5%)
Blunt liver injury: operation/NOM	10%/90%	8%/92%	14%/86%	29%/71%
Penetrating liver injury, 5,924 (% of penetrating injuries)	3,034 (51%)	1,224 (21%)	1,172 (20%)	494 (8%)
Operative mortality: blunt, penetrating	31%; 15%	28%; 10%	31%; 14%	56%; 38%

From 2022 American College of Surgeons Trauma Quality Improvement Program.

embolization in liver injury with attention toward its limitations and complications. Finally, a rational description of operative approach to specific patterns of high-grade liver injury is provided, along with the role for emerging techniques for hemorrhage control.

SURGICAL ANATOMY

From rapidly recognizing the severity of injury to executing an appropriate NOM plan or operative approach for hemostasis, a detailed understanding of liver anatomy is necessary for all steps of treatment. The principles of safe dissection and exposure, appropriate application of damage-control maneuvers, anatomic resection, decisions regarding the role of angioembolization, and even the likelihood of success of NOM depend upon anatomic considerations. To further complicate management, anatomy of the normal liver is highly variable, and surgeons may not have the benefit of cross-sectional imaging preoperatively to delineate an injury pattern relative to vascular and biliary structures.¹⁸ Anatomic variations (i.e., anomalous arterial inflow) may be particularly important during surgical exploration, where avoidance of iatrogenic injury to the uninvolved parenchymal, vascular, or biliary structures is of paramount importance.¹⁹ The arterial inflow to the liver is one of the most variable in the body (>40% anomalous right or left hepatic arteries), and surgical exploration must be performed avoiding injury to accessory or replaced arterial structures.²⁰

The usual configuration of eight anatomic segments divided into two hemilivers is dictated by hepatic venous anatomy, with the middle hepatic vein dividing the organ into the right and left lobes via Cantlie's line (main portal fissure) from the gallbladder fossa to the suprahepatic inferior vena cava (IVC; Supplemental Digital Content, Supplementary Data 1, <http://links.lww.com/TA/E611>). The portal triad consists of a hepatic artery branch, portal vein branch, and bile duct serving a lobe or segment. The mesothelial capsular tissue enclosing the liver (Glisson's capsule) also surrounds the portal triad, conferring structure and substance that are absent from the more delicate hepatic veins. The hepatic veins, both within the organ and along their short (5–20 mm) extrahepatic course before draining into the IVC, are more prone to tearing and more challenging to repair.²¹ Although injured hepatic arteries bleed, intraoperative exsanguination is generally due to major hepatic vein or IVC injury. Smaller but similarly delicate short hepatic veins drain directly into the vena cava and may cause significant bleeding.

GRADING SYSTEMS

Multiple grading systems for the severity of liver injury have been developed.²² The American Association for the Surgery of

Trauma (AAST) liver injury scale, which was first published in 1989, is most commonly applied.²³ The scale has subsequently undergone revisions, most recently in 2018, to better reflect the contribution of solid organ vascular injuries to morbidity and need for an operation²⁴ (Supplemental Digital Content, Supplementary Data 2, <http://links.lww.com/TA/E612>). The AAST system includes three components: operative, pathologic, and radiographic findings. Although the specific grading criteria are likely to be familiar to the readership of this review, it is worthwhile noting a few caveats to the I to V severity grading system. First, the AAST grading system relies purely on anatomic criteria to assign a grade. No consideration is given to the patient's physiology or other extra-anatomical factors. Second, specific patterns of vascular injury are assigned grades that suggest similarity in severity or complexity to other simpler (i.e., parenchymal) injuries. This leads several grades to be quite heterogeneous in terms of the injury patterns represented. For example, either severe parenchymal (>75% hepatic lobe disruption) or juxtahepatic caval injury qualifies as a grade V injury, and an actively bleeding vascular injury or 50% surface hematoma both qualify as a grade III injury. Finally, the scale only refers to injuries to the liver; roughly half of all deaths in patients with liver injury are from extrahepatic sources of mortality.²⁵ Therefore, the organ injury scale may be used for research or quality improvement but is neither designed nor adequate to inform patient treatment decisions alone.²⁶ These limitations underscore the importance of nuanced understanding of both anatomic and physiologic factors to optimize treatment planning.

DIAGNOSIS

In the acute setting, the presence and extent of complex liver injuries are typically delineated either (A) by multiphase computed tomography (CT) in the emergency department in the stable patient or (B) intraoperatively during abdominal exploration of the unstable patient. The latter is often with the adjunct of a positive Focused abdominal sonography for trauma (FAST) examination.

In blunt trauma patients who are hemodynamically stable, CT provides crucial information regarding the severity of parenchymal injury, presence and location of vascular injury, and other organs injured. It also elucidates common anatomic variants with ramifications for the surgical approach to the injured liver (i.e., replaced or accessory hepatic artery). The ideal CT protocol for characterizing liver anatomy, injuries, vascular injuries, and contrast extravasation includes arterial, portal venous, and delayed phases of imaging. Most trauma centers' whole body "pan scan" CT protocols for blunt trauma involve at least

two series after contrast injection and should be sufficient to evaluate involvement of the hepatic and portal veins, IVC, arteries, and associated contrast extravasation.²⁷

In the latter scenario presented in (B), patients with hemodynamic instability are taken directly to the operating room (OR). After initial tamponade of active bleeding sites, a thorough and systematic abdominal exploration should define the extent and location of injuries. In the absence of any indication to mobilize the liver or explore the retroperitoneum, the examination is typically limited to the surfaces of the organ and superficial inspection of the retroperitoneum. Examine and palpate the entire liver to define the size, anatomic distribution, and efflux of blood or bile from parenchymal lacerations. Then, examine the lesser sac for hematoma or bile, and visualize the cephalad portion of the right paracolic gutter to evaluate for central retroperitoneal hematoma. Careful documentation is important for future exploration and AAST organ injury scale grading. The latter may depend entirely on the surgeon's accurate description of injury.

Although the FAST examination is ubiquitous in the modern evaluation of trauma patients, its sensitivity remains 60% to 80%, and accuracy depends in part on operator experience.^{28–31} A positive FAST examination demonstrating hemoperitoneum in a hypotensive blunt trauma patient should be considered an indication for laparotomy, but a negative examination must not delay operation in the appropriate scenario.^{30,32}

INITIAL RESUSCITATION AND TRIAGE

Complex liver injuries showcase the importance of hemostatic and damage-control resuscitation.^{33,34} Limiting crystalloid infusion, balancing transfusions (or using whole blood), preventing coagulopathy, and permitting mild hypotension until hemostasis is achieved may constitute the difference between survival or exsanguination.

Early establishment of supradiaphragmatic venous access allows transfusion of whole blood or balanced component therapy. Preferred venous access is multiple upper-extremity large-bore peripheral catheters. Intraosseous or supradiaphragmatic central venous catheterization may be reserved for patients who fail peripheral catheterization or need central venous access for other indications (i.e., vasopressors perioperatively). Since substantial blood loss can be expected and synthetic dysfunction after major parenchymal injury may aggravate coagulopathy, a balanced transfusion and crystalloid-limited approach are crucial.

Avoidance of overresuscitation prior to hemorrhage control is critical to surviving complex liver injuries. Since patients with life-threatening hepatic venous or IVC injuries may rapidly exsanguinate when venous hydrostatic pressure is increased, mild hypovolemia with low/normal central venous filling pressures has been applied perioperatively. The hemostatic benefit from minimizing venous pressure prior to completion of parenchymal transection is well accepted in elective liver resection and can be applied for major hepatic injury.³⁵ Hypotensive resuscitation (i.e., systolic blood pressure ≤ 90 mm Hg and mean arterial pressure ≤ 60 mm Hg) until hemorrhage is surgically secured will help limit crystalloid administration and intraoperative hemorrhage from liver injury. Concomitant neurologic injury is generally considered a contraindication.³⁶ Protracted or profound hypotension after major injury will aggravate acidemia and coagulopathy and should be avoided.³⁷

NONOPERATIVE MANAGEMENT

The injured patient's physiology remains the cardinal criterion for initial nonoperative versus immediate operative management. The patient with liver injury, hemodynamic normality, and without other indication (i.e., additional injuries) for immediate operation may be appropriate for initial NOM. Multiple studies support NOM as the initial treatment for hemodynamically normal patients or patients who are responders to resuscitation (promptly achieve hemodynamic stability after initial resuscitation) with blunt liver injuries, irrespective of the grade of injury^{7,10,12,38,39} (Fig. 1). This may include major venous injury. Nonoperative management has also been applied in penetrating liver injury in the stable patient without hollow visceral injury.^{9,40–42} Computed tomography imaging will help define trajectory for gunshot injuries managed nonoperatively. Multiple series have identified high injury grade (i.e., AAST IV and V) as a risk factor for NOM failure. Therefore, patients with these complex injury patterns should be considered high risk.^{7,13,25,37–44} In general terms, these patients should be admitted to an intensive care unit (ICU), undergo frequent reassessments including laboratory studies, and be closely monitored for early signs of failure or complications requiring intervention. More specifics, including recommendation for laboratory study and vital sign reassessment intervals, timing of enteral nutrition, and longer-term activity restrictions, are outlined in a recent Western Trauma Association critical decisions algorithm³⁹ (Table 2).

The benefit of a short-term routine interval CT after successful initial NOM of complex liver injury is controversial.^{45–47} The lack of evidence of overall benefit in large series, most of which included all grades of liver injury, suggests interval CT only when the patient manifests an indication for repeat CT; a paucity of patients had actionable lesions on repeat scans.^{48,49} However, as modern studies demonstrate greater than 10% incidence of pseudoaneurysm following grades III to V liver injuries, 48- to 72-hour interval multiphase CT may benefit patients with complex injuries.^{50,51} Since over 90% of complications requiring intervention (angioembolization, endoscopic retrograde cholangiography/stent placement, percutaneous drainage of hepatic abscesses, or bilomas) occur with grades IV and V liver injuries and such a need is the rule rather than the exception with grade V injury, preemptive recognition and treatment in this high-risk group seem appropriate.^{52,53} Guidelines from both the Western Trauma Association and Panamerican Trauma Society support this approach.^{39,54}

ANGIOEMBOLIZATION: BENEFITS AND COMPLICATIONS

The paradigm shift to predominantly NOM of hepatic injuries (1990–2000s) produced a reliance on the angioembolization that endures today.⁵⁵ Refinement of embolization materials and techniques (i.e., selective versus superselective embolization procedures) improved hemostatic success and decreased ischemic complications.^{56,57} Recent data suggest that selective hepatic artery compared with proximal angioembolization results in fewer hepatic complications.⁵⁸

With the acknowledged limitations of angioembolization, recent retrospective studies describe angioembolization safety

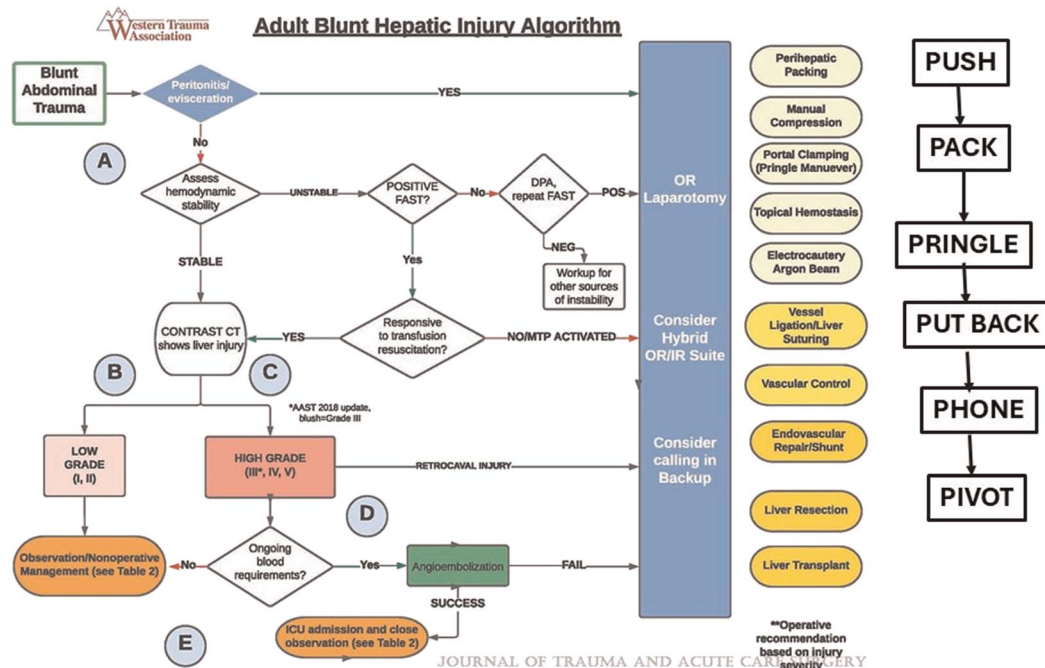


Figure 1. Western Trauma Association algorithm for the diagnosis and management of blunt hepatic injury in adults. Circled letters correspond to lettered sections in the article's text. The 6 Ps approach to the operative management of liver injury has been added. IR, interventional radiology (with permission from Ref. ³⁹).

and efficacy in high-grade injuries to guide decision making. Angioembolization is an effective adjunct to NOM of grades III to V injuries and may decrease mortality when combined with surgery.^{59,60} Angioembolization stops arterial hemorrhage,

with resolution of hemorrhage in over 90% of cases.⁶¹ Early embolization is also associated with a significant decrease in transfusion requirements. Rebleeding after postoperative angioembolization is more common with penetrating than blunt injury.²⁶

TABLE 2. Western Trauma Association Blunt Hepatic Injury Guideline for Nonoperative and Postintervention Management

AAST Grade	Low Grade	High Grade
	I and II	III, IV, and V
ICU	No	Yes — 24 h minimum*
Laboratories	Every 12 h until stable × 2	CBC — every 6 h until stable × 2, LFTs
Monitoring	Vital signs every 4 h	Vital signs every 1 h Continuous heart rate with every 2-h BP check
Diet	Diet ad lib as tolerated Clear liquid diet for 12 h	NPO × 12 h
VTE prophylaxis	Start within 24 h of stable Hgb	Start within 24–48 h of stable Hgb
Follow-up contrast CT scan	Clinical change (sepsis, abdominal pain, jaundice) Laboratory change (elevated transaminases or decrease in Hgb)	Clinical change (sepsis, abdominal pain, jaundice) Laboratory change (elevated transaminases or decrease in Hgb) Consider screening CT at 3–5 d before discharge to evaluate for PSA, AVF, biliary issues
Biloma/bile leak	ERCP/IR	ERCP/IR Surgical management if recurrent, failure of NOM
Abscess	Drain/IR Surgical management if recurrent, failure of NOM	Drain/IR Surgical management if recurrent, failure of NOM
Discharge criteria (minimum admission time)	Stable Hgb 24 h from injury Tolerating oral intake	Stable Hgb 72 h from injury Tolerating oral intake
Return to normal activity	Grade + 2 = weeks to return	6 wk and clinical clearance by MD

*Select high-grade injuries without evidence of hemorrhage may not require ICU admission.

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AVF, arteriovenous fistula; BP, blood pressure; CBC, complete blood count; ERCP, endoscopic retrograde cholangiopancreatography; Hb, hemoglobin; IR, interventional radiology; LFT, liver function test; MD, medical doctor; NPO, nothing by mouth; PSA, pseudoaneurysm; VTE, venous thromboembolism.

It is important to consider the limitations and the potential complications of angioembolization, especially in the stable patient.^{55–64} Local complications are related to arterial cannulation. Complex injuries carry a risk of early and delayed failures, often related to venous hemorrhage requiring laparotomy.⁶³ The liver-specific complication rate (biloma, necrosis, abscess) of embolization has varied considerably in single-center studies, from 7% to 94%. Angioembolization may cause major hepatic necrosis and life-threatening sepsis due to ischemia.^{55–64} This is a common complication in NOM; ranging from 0% to 42% (mean, 16%) of patients undergoing angioembolization developed hepatic necrosis.^{64,65} However, a recent multicenter study also demonstrated a 44% overall rate of liver-related complications in both patients who underwent NOM with angioembolization compared with those who did not.^{66,67} Mortality was also similar between embolized and noninterventional groups. With selection bias and injury severity as obvious confounders, it may not be possible to quantify the independent contribution of angioembolization to major complications.

The sum of the best available evidence suggests that angioembolization is an effective hemostatic adjunct to both nonoperative and surgical management for grades III to V injuries (especially those with radiographic evidence of ongoing arterial hemorrhage) while conferring an additional risk of complications. Consideration must be given to the radiographic characteristics of the injury, transfusion requirement, plans for (or confirmation of) surgical hemostasis, and likelihood of complications for each case.^{55–67}

OPERATIVE MANAGEMENT: WHAT YOU NEED TO KNOW

Surgical management of complex liver injuries can be parsed into an early (“initial operation”) and a later operation (return to the operating room [RTOR]).^{10,13} The priorities, objectives, and usual procedures performed in each phase differ. Patients who meet criteria for emergency laparotomy for liver hemorrhage control (initial OR, at the time of presentation) typically benefit from damage-control techniques and a second look at RTOR, typically after shock resolves 24 to 48 hours after presentation. Drastically increased reliance on NOM has predictably resulted in waning surgical experience.

Initial Operation

In the hemodynamically unstable trauma patient with concern for liver injury, initial venous access and resuscitation described previously and preparation for surgery are performed contemporaneously. The patient is positioned supine with arms out. The chest and abdomen are both included in the field in case the laparotomy must be extended to sternotomy for adequate intrapericardial IVC exposure. A midline laparotomy incision provides adequate exposure of all quadrants of the abdomen. A right subcostal extension can improve access to the juxtahepatic veins and the posterior right lobe. A self-retaining retractor is essential, providing both cephalad pull and anterior lift of the lower ribs. In the uncommon stable patient with preoperatively confirmed isolated liver injury, a small bump under the right chest and a right subcostal (Kocher) incision with the right arm tucked may optimize access.

An escalating protocol for operative management is critical in the management of major liver injury.^{10,13} The paramount goal in initial operative management of a liver injury is to stop the bleeding—save a life. Definitive management of a liver injury in the unstable patient should be deferred until RTOR after the initial damage-control procedure. Upon entering the abdomen, perform systematic packing and four-quadrant exploration to quickly delineate life-threatening injuries. Only peripheral, anterior hepatic lacerations will be noted on this cursory examination; packing can provide hemostasis while major hemorrhage is identified and temporized elsewhere. Since relatively minor liver lacerations are common in blunt trauma and are distractingly obvious on brief examination, avoid treating minor liver hemorrhage while another source of bleeding goes unaddressed. After excluding other sources of life-threatening hemorrhage, a detailed examination of the right upper quadrant begins by inspecting the visible surfaces of the liver and palpating all surfaces. As with any trauma laparotomy, the most compelling bleeding sites should be addressed first.

Over 80% to 85% of liver injuries encountered intraoperatively during the initial OR procedure can be successfully managed with basic maneuvers. We suggest an operative approach to liver injury applying the 6 Ps: Push, Pack, Pringle, Put back, Phone for additional surgical assistance, and Pivot (Fig. 1). The initial maneuver to treat an actively bleeding liver injury is to compress the two lobes of the liver back to normal anatomy and then push the liver posteriorly. This provides temporary tamponade for the majority of liver injuries (including major venous), provides the anesthesia team with time to resuscitate the patient, and allows the surgeon to develop an operative plan.

Second, pack the liver (i.e., perihepatic packing around the organ) to provide extrinsic compression. Do not aggravate bleeding by packing into lacerations. If packing provides hemostasis in the hemodynamically compromised patient, truncate the operation and complete damage control. The patient will generally survive the operation if packing is effective and applied early. Packing invoked late in the acidotic, coagulopathic patient will not salvage the patient. If the liver bleeds through packing, apply the Pringle maneuver. Temporary occlusion of the porta hepatis quells hemorrhage from portal venous and arterial sources, providing both therapeutic and diagnostic benefits. Arterial hemorrhage deep in the liver parenchyma while the porta is occluded may be amenable to selective ligation if visualization is sufficient. Visualization is facilitated by hepatotomy with finger fracture technique or a stapling device.⁶⁸ Available hemostatic techniques include cautery (monopolar, argon beam coagulation, or bipolar radiofrequency device [i.e., Aquamantys]) and application of topical hemostatic agents. Large liver sutures should be avoided if possible to minimize hepatic necrosis; selective intrahepatic vascular ligation is preferable. Postoperative angioembolization is also a consideration with concern for arterial injury. If hemostasis is adequate after these maneuvers, resuscitate and optimize the patient in the ICU in preparation for RTOR in 24 to 48 hours.

However, ongoing hemorrhage with perihepatic packing and the porta occluded suggests bleeding from a major hepatic venous or IVC injury that will require advanced techniques, the most skilled assistance available (i.e., “Phone” for help), and preparation for major blood loss and resuscitation. This dark

consistent bleeding through packs despite the described maneuvers also invokes “put” the liver back in its anatomic position, with anterior-to-posterior pressure to compress the hepatic venous outflow and juxtahepatic IVC as much as possible. Again, allow the anesthesia team time to catch up with transfusion requirements and to obtain additional blood products. Then, quickly prepare to “pivot” to a more complex operation. Prompt recognition and the pivot to a more advanced operative approach with appropriate surgical expertise necessary to do so are critical for saving these patients with complex liver injuries.⁶⁹

All available resources should be requested by this point, including the most experienced surgical assistance available and protocolized massive transfusion services. Involve hepatobiliary or liver transplant surgeons in the index operation for complex injuries, if available. The operation most commonly required at this point for patients who continue to bleed despite the aforementioned maneuvers is exposure and repair of a juxtahepatic IVC injury or hepatic venous injury. A critical concept in this discussion is that the heterogeneity of venous injuries demands multiple management options. A more nuanced operative approach than is generally applied is necessary for management of juxtahepatic venous injuries.^{10,13,21,68–72} A direct approach to these major venous injuries is preferred, with avoidance of lobectomy if possible. Management of an intraparenchymal hepatic vein injury is generally accomplished with compression and packing as definitive management (or even NOM). If packing fails, direct access to an injured intraparenchymal hepatic vein injury may require hepatotomy with finger fracture or stapling techniques. The exsanguinating juxtahepatic injury must be recognized promptly on entry into the abdomen. Profuse venous hemorrhage from behind or above the liver suggests injury to the retrohepatic vena cava, suprahepatic IVC, or extraparenchymal major hepatic veins. Anatomic lobectomy at initial laparotomy in the physiologically compromised patient should be avoided, as it still carries 25% to 50% mortality. Lobectomy in this setting is appropriate only in the rare circumstance where the parenchymal and/or venous injuries mandate it.

When encountering uncontrolled exsanguinating major hepatic or venous injury despite pushing the liver and packing as described, immediate hepatic vascular isolation may be required. Control of the short suprahepatic IVC is the initial step. With currently available operative techniques and expertise, this can generally be accomplished intra-abdominally. Performing a right thoracotomy or sternotomy in the critically ill patient with major hepatic/venous injury adds time and morbidity that such

patients cannot tolerate. The porta hepatis should already be occluded. Intermittent, rather than constant, portal clamping may be applied; that is, 10 to 15 minutes on, 5 minutes off.^{68,73,74} Two maneuvers provide access to the suprahepatic IVC without mobilization of the liver. The most direct is with division of the falciform ligament anterior to posterior until visualization of the three hepatic veins (Fig. 2). More proximal control of the suprahepatic vena cava can also be established through the central diaphragm and pericardium without a sternotomy (Fig. 3). Next, the infrahepatic IVC (cephalad to the renal veins) is accessed from either the left or the right; a finger can be used to develop a tunnel to allow control at this level by admitting a vascular clamp or vessel loop. We generally do not clamp the abdominal aorta (or utilize a resuscitative endovascular balloon occlusion of the aorta) in this situation as a component of hepatic vascular isolation; it may be necessary if the patient does not tolerate IVC occlusion. Use of resuscitative endovascular balloon occlusion of the aorta in the management of liver injury is controversial and may increase mortality.^{75–77} Venovenous bypass can be helpful but is uncommonly necessary or immediately available.

Under more controlled circumstances, mobilization of the liver may be required to provide exposure of a major parenchymal or venous injury. Begin with division of the falciform ligament, avoiding injury to the hepatic veins that lie far posterior along the ligament, well after it divides into two leaflets. The left triangular and coronary ligaments can be divided with cautery or scissors by opening the gastrohepatic ligament, avoiding injury to the phrenic vein, left hepatic vein, or an anomalous left hepatic artery. The right side of the liver may be mobilized by dividing the right triangular and coronary ligaments, retracting the right lobe toward the patient's left side, and clipping and dividing short hepatic veins.

Endovascular techniques provide multiple options in the management of major venous injuries. Percutaneous stent placement can provide definitive treatment of major juxtahepatic venous injuries. Endovascular balloon occlusion of the IVC is a promising adjunct to open surgical exposure and control of this challenging injury.^{75–78} Partial or complete IVC balloon occlusion may temporarily slow or stop hemorrhage to allow better exposure and visualization of an injury.^{75,78} Although experience is limited with endovascular techniques for major hepatic venous injury and there may be logistical challenges (i.e., angiography for placement), it represents an exciting advance in managing this deadly injury pattern.

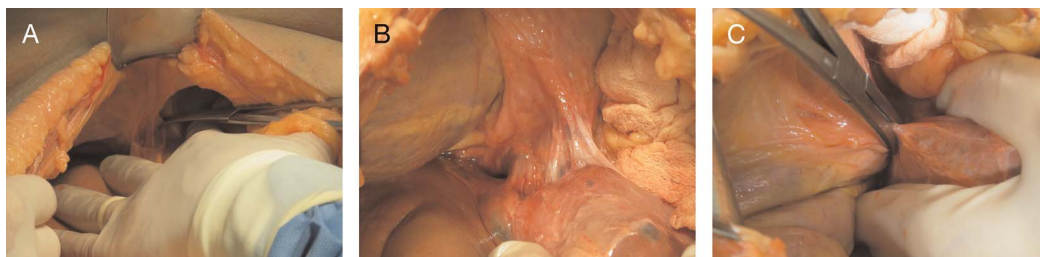


Figure 2. The most direct approach for intra-abdominal control of the suprahepatic IVC starts with (A) division of the falciform ligament and its posterior leaflets anterior to posterior until (B) visualization of the blue hue of the three hepatic veins. (C) While retracting the liver anteriorly and caudally with your nondominant hand, place a vascular clamp and carefully close it on the suprahepatic IVC when the tips touch the spine.

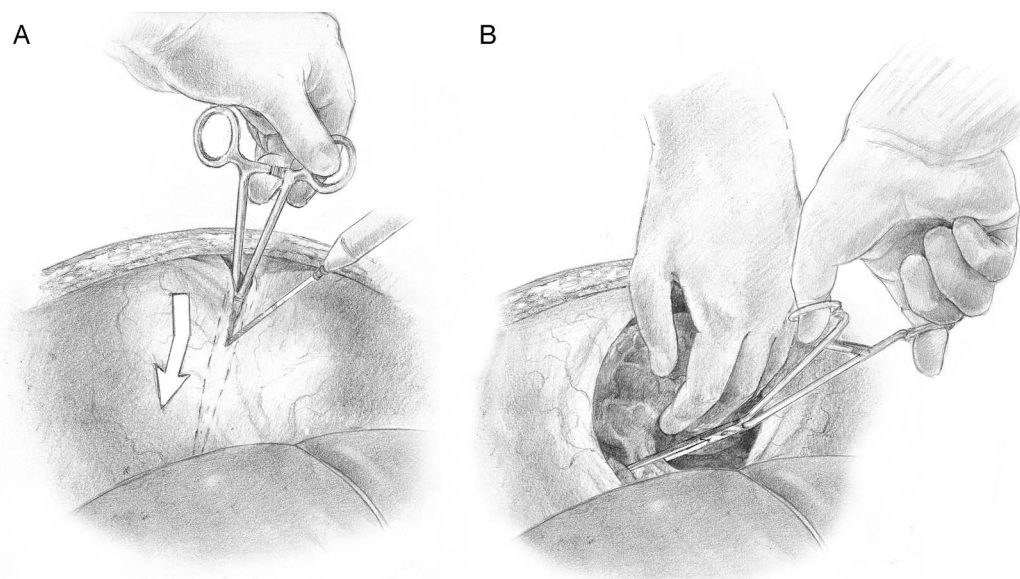


Figure 3. Intraoperative control of the IVC via intra-abdominal approach. (A) The pericardium is bluntly dissected from the posterior aspect of the sternum. A small hole is made in the diaphragmatic pericardium as superiorly as possible. Be careful to avoid injury to the heart with this maneuver. With a clamp protecting the heart, the electrocautery or scissors is used to split the diaphragm/pericardium posteriorly. Curve toward the right as you approach entry of the IVC into the pericardium. (B) The heart is lifted cephalad and anteriorly; a vascular clamp is placed on the IVC. The IVC should be clamped at an angle to ensure clamping of the entire vein; an angled Potts or IVC clamp is best (with permission from Ref. ¹¹).

The operative principles and approaches described above apply to penetrating liver as well as blunt mechanisms. A higher proportion of penetrating versus blunt injuries undergo laparotomy at every grade (2022 Trauma Quality Improvement Program review). However, indications for laparotomy for penetrating injuries beyond hemodynamic instability are more often for transperitoneal penetration, trajectory, weapon, and concern for hollow viscus injury. With central penetrating injury to the liver, balloon tamponade is a simple and effective technique to achieve hemostasis.^{79–82} This is an effective technique with transfixing (through and through) hepatic gunshot wounds (GSWs) with bleeding from both ends. This technique can use a Blakemore balloon or a red rubber catheter and Penrose drain device to tamponade the bleeding (Fig. 4). A Penrose drain measuring 1 × 12 inch and 12-Fr red rubber catheter provide the most sim-

ple and readily available tool. The balloon may be left in place for several days, to allow clot formation and stabilization of the patient.^{79–83}

After hemostasis is achieved at the initial operation and damage control applied, the patient should be transported to the ICU for ongoing resuscitation, postoperative CT, and potential angioembolization pending stability and CT findings. The postoperative CT will also reveal ischemic hepatic parenchyma, which may require resection at RTOR. Although controversial, routine postoperative CT at 5 to 7 days has been advocated to evaluate for early complications that may require intervention, that is, biloma or pseudoaneurysm.⁸³ Such complications are relatively common after any liver injury requiring surgery, with one series reporting 70% morbidity following laparotomy for blunt liver trauma, regardless of grade.⁸⁴

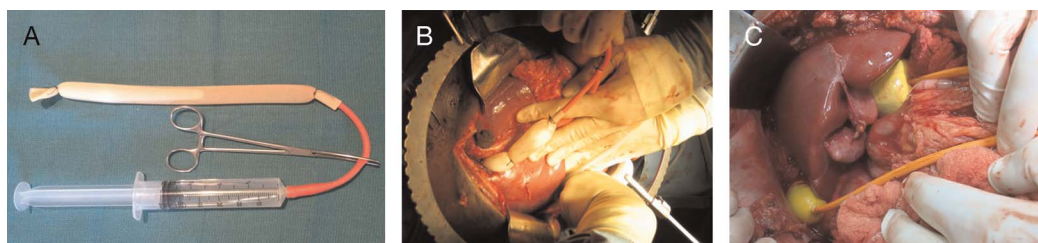


Figure 4. Penrose drain/red rubber catheter or Sengstaken-Blakemore tube for balloon tamponade of penetrating central liver injury. (A) Penrose drain balloon device consists of 12-Fr red rubber catheter and 1-inch Penrose drain. Close one end of the Penrose drain with a 2-0 silk suture and then insert the catheter into the drain. At a distance 6-cm longer than the length of the central hepatic wound, tie another 2-0 silk to provide a watertight system. (B) Next, insert the device into the tract, leaving 2 to 3 cm of balloon on either end of the tract. Inflate the balloon with normal saline until tamponade is achieved (with permission from Ref. ⁷⁹). (C) Both ends of a Sengstaken-Blakemore balloon are visible after placement for a transfixing (through and through) central gunshot to the liver (with permission from Ref. ⁸²).

Return to the Operating Room

Crucial operative objectives for the second look laparotomy following damage-control surgery for hepatic trauma include the following: stop any further bleeding, identify and oversee macroscopic bile leaks (with or without parenchymal resection), resect necrotic parenchyma (nonanatomic or anatomic resections), place closed suction drains, and close the abdomen. Involving liver surgical subspecialists in both the planning and operative portions of this procedure is prudent.^{13,85} Under controlled circumstances where hemostasis is achieved, a two-step cholangiogram via the cystic duct remnant after cholecystectomy is performed. Methylene blue or saline cholangiography will demonstrate bile duct leaks from the cut or injured liver edges. Meticulous oversewing of these bile leaks may prevent late morbidity. The second step is formal water-soluble iodinated contrast cholangiography. Based on the location and size of a bile duct injury, treatment may include repair or hepatic resection. With hepatobiliary expertise at RTOR, anatomic resection of necrotic hepatic parenchyma based on significant volume of ischemic segments noted on CT or intraoperative findings may afford fewer postoperative complications and secondary interventions than more conservative nonresectional treatments of nonviable liver parenchyma.^{13,85,86} Rarely, hepatectomy and liver transplantation may be required.⁸⁶ Drains are placed to detect and evacuate any bile leak after abdominal closure.

Omental packing has been applied at both initial laparotomy and RTOR.^{25,87} (We uncommonly use this technique.^{10,11,13}) The concept is to fill the dead space with viable tissue and to tamponade minor venous oozing. After adequate debridement and control of surgical bleeding, a vascularized omental pedicle can be placed in the area of parenchymal liver injury. The omental pedicle can be based on either the right or left gastroepiploic artery. The omental pedicle is placed within the hepatic defect, and the edges of the liver are loosely approximated with either running or interrupted sutures at least 2.5 cm from the liver edge (Supplemental Digital Content, Supplementary Fig. 1A, <http://links.lww.com/TA/E613>, and Supplementary Fig. 1B, <http://links.lww.com/TA/E614>).

Management of abdominal closure after liver injury can be challenging because of edema and gaseous distension of the viscera. Every effort should be made to close the fascia primarily. The Centers for Disease Control wound classification if bile ducts were involved in injury or resection is at least clean contaminated given biliary contamination.⁸⁸ Skin closure can be considered if no further contamination beyond liver injury was encountered and conditions for wound healing are otherwise favorable.

COMPLICATIONS

Complications after both surgical and NOM of complex liver injuries are common and increase with injury severity. Surgeons managing patients nonoperatively must be familiar with the most common and dangerous complications associated with NOM. In a large multicenter cohort study of complex injuries managed nonoperatively, liver-specific complications developed in 5% of patients with grade 3 injury, 22% with grade 4 injury, and 52% with grade 5 injury.⁸⁹ The patient's 24-hour red blood cell transfusion requirement was also a risk factor for complications. The most common early complications observed were

vascular (pseudoaneurysm and delayed hemorrhage), biliary (leak/biloma, biliovenous fistula, biliopleural fistula), and infectious in nature (abscess or necrosis with sepsis) and abdominal compartment syndrome. Most of these complications are managed with angioembolization, percutaneous drainage, or endoscopic retrograde cholangiography/stent. Although operative mortality is higher for blunt compared with penetrating mechanisms of liver injury, postoperative hepatic infectious and biliary complications and need for repeat interventions are more frequent after GSWs.^{22,86,90–94} The higher frequency of hollow viscus injury with penetrating injury contributes to this infection risk. A postoperative complication rate for hepatic GSWs as high as 74% was reported.⁹⁵ Routine postoperative CT within 7 days of operation significantly decreased the rate of overall morbidity. The difference was due to early diagnosis and treatment of abscesses, anastomotic leaks, and missed injuries. Laparoscopy with abdominal washout and establishment of external drainage has also been applied to manage bile peritonitis in patients failing NOM.^{96,97} Laparotomy is necessary less often in this setting. Given the relative frequency of these events, it is crucial that the admitting hospital has immediate and reliable access to intensive care, transfusion, trauma and hepatobiliary surgery, angiography, and advanced endoscopic services. Facilities without such services should consider prompt transfer to a center with trauma and hepatobiliary expertise.⁹⁰

CONCLUSION

Eighty-five to 90% of patients with blunt liver injuries can be managed nonoperatively. Complications requiring intervention are common in patients with high-grade liver injuries. Substantial room for improvement remains in the operative care of the patient with hemodynamic instability or who fails NOM. We suggest the 6 Ps as an approach to the initial operative management of the bleeding liver. Simple maneuvers tamponade bleeding in 80% to 85% of cases. More advanced techniques and hepatobiliary expertise (if available) are necessary for the most complex liver injuries. The complexity and infrequency

TABLE 3. Current Recommendations for Operative Management of Liver Injuries

Operate on the patient who needs an operation
Rescue the patient who requires rescue
Good exposure, self-retaining retractor, best help available
The cardinal goal of the index operation is to stop the bleeding
Early recognition and treatment of the exsanguinating juxtahepatic venous injury
Be a minimalist. Basic maneuvers tamponade bleeding in 85% of cases.
6 Ps: Push–Pack–Pringle–Put back–Phone–Pivot
Allow anesthesia time to resuscitate the patient during the Push maneuver
If Packing and Pringle do not control bleeding, prompt Pivot to a more complex operation providing the necessary skills determines whether these patient live or die
Central hepatic GSWs can be managed with balloon tamponade
Avoid anatomic resection at the initial operation
Definitive management of the liver injury is the goal of RTOR
Hepatic resection rather than nonresectional operation at RTOR may reduce complications and the need for repeated interventions
Juxtahepatic venous injuries are heterogeneous; their operative management must be appropriate for the anatomic injury

of these high-grade injuries, collectively waning experience with surgical treatment of juxtahepatic caval and hepatic venous injuries, and siloing of trauma and hepatobiliary surgical specialists compound the operative challenges. To combat these issues, surgeons must maximize their knowledge of and preparation for managing these injuries, both in and outside of the OR (Table 3).

AUTHORSHIP

C.R.R. and A.B.P. contributed in the conception and study design. C.R.R. and A.B.P. contributed in the literature review. C.R.R., J.B.B., and A.B.P. contributed in the data acquisition. C.R.R., J.B.B., and A.B.P. contributed in the data analysis and interpretation. C.R.R., J.B.B., and A.B.P. contributed in the drafting of the manuscript. C.R.R., J.B.B., and A.B.P. contributed in the critical revision.

DISCLOSURE

Conflicts of Interest: Author Disclosure forms have been supplied and are provided as Supplemental Digital Content (<http://links.lww.com/TA/E615>).

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